

# Diagnosing Degenerate Higgs Bosons at 125 GeV

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We develop diagnostic tools that would provide incontrovertible evidence for the presence of more than one Higgs boson near 125 GeV in the LHC data.

Keywords: Supersymmetry phenomenology, Higgs physics

Data from the ATLAS and CMS collaborations [1, 2] provide an essentially  $5\sigma$  signal for a Higgs-like resonance with mass of order 123–128 GeV. Meanwhile, the CDF and D0 experiments have announced new results [3], based mainly on  $Vh$  associated production with  $h \rightarrow b\bar{b}$ , that support the  $\sim 125$  GeV Higgs-like signal. While it is certainly possible that the observed signals in the various production/decay channels will converge towards their respective Standard Model (SM) values, the current central values for these channels deviate by about  $1\text{--}2\sigma$  from SM predictions. Clearly, a prime goal of future LHC data taking will be increased statistics, sufficient to clearly rule out or confirm a SM nature for this Higgs-like signal. Meanwhile, it is very interesting to discuss models in which the observed central values for the various channels deviate from the SM along the lines seen in the data.

One of the most significant deviations in the current data is the enhancement in the  $\gamma\gamma$  final state for both gluon fusion ( $gg$ ) and vector boson fusion (VBF) production. Such enhancement can be obtained in a variety of models and is often associated with the observed mass eigenstate at  $\sim 125$  GeV mixing with a nearby (unobserved or degenerate) state. A particularly appealing supersymmetric model that easily obtains both a Higgs mass of order 125 GeV and significant  $\gamma\gamma$  mode enhancements is the Next-to-Minimal Supersymmetric Standard Model (NMSSM). The NMSSM is very attractive since it solves the  $\mu$  problem of the minimal supersymmetric extension of the SM (MSSM): the ad hoc parameter  $\mu$  appearing in the MSSM superpotential term  $\mu\hat{H}_u\hat{H}_d$  is automatically generated in the NMSSM from the  $\lambda\hat{S}\hat{H}_u\hat{H}_d$  superpotential term when the scalar component  $S$  of  $\hat{S}$  develops a VEV  $\langle S \rangle = s$ :  $\mu_{\text{eff}} = \lambda s$ . The three CP-even Higgs fields,  $H_u$ ,  $H_d$  and  $S$  mix and yield the mass eigenstates  $h_1$ ,  $h_2$  and  $h_3$ . A 125 GeV Higgs state with enhanced  $\gamma\gamma$  signal rate is easily obtained for large  $\lambda$  and small  $\tan\beta$  [4]. The  $h_1$  and  $h_2$  are typically close in mass in this case, with one of them being primarily the doublet-like  $H_d$  while the other has a large singlet  $S$  component. A particularly interesting case arises when the  $h_1$  and  $h_2$  are nearly degenerate [5].

A very crucial issue is then how to determine whether or not there are two (or more) Higgs bosons versus just one contributing to the Higgs signals at 125 GeV. One possibility, requiring high statistics given the experimental resolution (of order  $\gtrsim 1.5$  GeV), is that the mass peaks in the  $\gamma\gamma$  and  $4\ell$  final states would display a structure of two overlapping peaks. However, for many of the degenerate scenarios it turns out that the  $\gamma\gamma$  and  $4\ell$  final states are dominated by only one of the degenerate Higgses, and the other one would show up primarily in  $b\bar{b}$  and/or  $\tau\tau$  final states. However, mass resolutions in these channels are very poor and detection of a two peak structure using invariant mass distributions would appear to be very difficult. A direct probe of this kind of degeneracy using the full complement of final states is clearly highly desirable.

In this Letter, we therefore develop diagnostic tools that would reveal the presence of two Higgs bosons even if they are extremely close in mass. We illustrate our technique using the NMSSM scenarios generated for [5] (where NMSSM parameter ranges and all constraints are discussed in detail) in which the two lightest CP-even Higgs bosons,  $h_1$  and  $h_2$ , both lie in the 123–128 GeV mass window. The diagnostic tools we suggest are however fully general and can be employed for any model which produces approximately degenerate Higgs states.

The main production/decay channels relevant for current LHC data are  $gg$  and VBF with Higgs decay to  $\gamma\gamma$  or  $ZZ^* \rightarrow 4\ell$ . The LHC also probes  $W, Z$ +Higgs with Higgs decay to  $b\bar{b}$ , a channel for which Tevatron data is relevant, and  $WW \rightarrow \text{Higgs}$  with Higgs  $\rightarrow \tau^+\tau^-$ . We compute the ratio of the  $gg$  or VBF induced Higgs cross section times the Higgs branching ratio to a given final state  $X$ , relative to the corresponding value for the SM Higgs boson, as

$$R_{gg}^{h_i}(X) \equiv \frac{\Gamma(h_i \rightarrow gg) \text{BR}(h_i \rightarrow X)}{\Gamma(h_{\text{SM}} \rightarrow gg) \text{BR}(h_{\text{SM}} \rightarrow X)}, \quad R_{\text{VBF}}^{h_i}(X) \equiv \frac{\Gamma(h_i \rightarrow WW) \text{BR}(h_i \rightarrow X)}{\Gamma(h_{\text{SM}} \rightarrow WW) \text{BR}(h_{\text{SM}} \rightarrow X)}, \quad (1)$$

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where  $h_i$  is the  $i^{th}$  NMSSM scalar Higgs, and  $h_{SM}$  is the SM Higgs boson. Note that the corresponding ratio for  $V^* \rightarrow V h_i$  ( $V = W, Z$ ) with  $h_i \rightarrow X$  is equal to  $R_{VBF}^{h_i}(X)$ . For the cases studied, where there are two nearly degenerate Higgs bosons, we then compute the net signal and the effective Higgs mass, respectively, in given production and final decay channels  $Y$  and  $X$ , respectively, as

$$R_Y^h(X) = R_Y^{h_1}(X) + R_Y^{h_2}(X), \quad m_h^Y(X) \equiv \frac{R_Y^{h_1}(X)m_{h_1} + R_Y^{h_2}(X)m_{h_2}}{R_Y^{h_1}(X) + R_Y^{h_2}(X)}. \quad (2)$$

Of course, the extent to which it is appropriate to combine the rates from the  $h_1$  and  $h_2$  depends upon the degree of degeneracy and the experimental resolution. For the latter, it is useful to keep in mind the value  $\sigma_{res} \sim 1.5$  GeV [6]. It should be noted that the widths of the  $h_1$  and  $h_2$  are of the same order of magnitude as the width of a 125 GeV SM Higgs boson (a few MeV), *i.e.* very much smaller than this resolution.

In the context of any two-Higgs-doublet plus singlets model, not all the  $R^{h_i}$  are independent. For example,  $R_{VH}^{h_i}(X) = R_{VBF}^{h_i}(X)$ ,  $R_Y^{h_i}(\tau\tau) = R_Y^{h_i}(bb)$  and  $R_Y^{h_i}(ZZ) = R_Y^{h_i}(WW)$ , and similiary for the  $R^h$ 's. A complete independent set of  $R^h$ 's can be taken to be:

$$R_{gg}^h(WW), \quad R_{gg}^h(bb), \quad R_{gg}^h(\gamma\gamma), \quad R_{VBF}^h(WW), \quad R_{VBF}^h(bb), \quad R_{VBF}^h(\gamma\gamma). \quad (3)$$

Let us now look in more detail at a given  $R_Y^h(X)$ . It takes the form

$$R_Y^h(X) = \sum_{i=1,2} \frac{C_Y^i C_X^i}{C_\Gamma^i} \quad (4)$$

where  $C_X^i$  is the coupling strength for  $h_i \rightarrow X$  squared relative to the SM value and  $C_\Gamma^i$  is the ratio of the total width of the  $h_i$  to the SM Higgs total width. The diagnostic tools that we propose to reveal the existence of a second, quasi-degenerate (but non-interfering in the small width approximation) Higgs state are the double ratios:

$$\text{I): } \frac{R_{VBF}^h(\gamma\gamma)/R_{gg}^h(\gamma\gamma)}{R_{VBF}^h(bb)/R_{gg}^h(bb)}, \quad \text{II): } \frac{R_{VBF}^h(\gamma\gamma)/R_{gg}^h(\gamma\gamma)}{R_{VBF}^h(WW)/R_{gg}^h(WW)}, \quad \text{III): } \frac{R_{VBF}^h(WW)/R_{gg}^h(WW)}{R_{VBF}^h(bb)/R_{gg}^h(bb)}, \quad (5)$$

each of which should be unity if only a single Higgs boson is present but which are generally expected to deviate from 1 if two (or more) Higgs bosons are contributing to the net  $h$  signals. One can check that all other double ratios that are equal to unity for single Higgs exchange are not independent of the above three. Of course, in a model that does not have a two-doublet plus singlet structure, the relations among  $R$ 's quoted above will not necessarily apply and additional double ratios that reduce to unity in the case of single Higgs exchange may prove useful.

To explore how powerful these double ratios are in practice, we turn to the NMSSM scenarios with semi-unified GUT scale soft-SUSY-breaking sampled in [5].<sup>1</sup> These scenarios obey all experimental constraints (including  $\Omega h^2 < 0.136$  and 2011 XENON100 constraints on the spin-independent scattering cross section) except that the SUSY contribution to the anomalous magnetic moment of the muon,  $\delta a_\mu$ , is too small to explain the discrepancy between the observed value  $a_\mu$  and that predicted by the SM. For a full discussion of the kind of NMSSM model employed see also [7, 8].

In Fig. 1, we plot the numerator versus the denominator of the double ratios I) and II), III) being very like I) due to the correlation between the  $R_{gg}^h(\gamma\gamma)$  and  $R_{gg}^h(WW)$  values discussed in [5]. We observe that these double ratios will often deviate from unity (the diagonal dashed line in the figure). The probability of such deviation increases dramatically if we require (as apparently preferred by LHC data)  $R_{gg}^h(\gamma\gamma) > 1$ , see the solid (vs. open) symbols of Fig. 1. This is further elucidated in Fig. 2 where we display the double ratios I) and II) as functions of  $R_{gg}^h(\gamma\gamma)$  (left plots) and  $\max[R_{gg}^{h_1}(\gamma\gamma), R_{gg}^{h_2}(\gamma\gamma)]/R_{gg}^h(\gamma\gamma)$  (right plots). For the NMSSM, it seems that the double ratio I) provides the greatest discrimination between degenerate vs. non-degenerate scenarios with values very substantially different from unity (the dashed line) for the majority of the degenerate NMSSM scenarios explored in [5] that have enhanced  $\gamma\gamma$  rates. Note in particular that I), being sensitive to the  $b\bar{b}$  final state, singles out degenerate Higgs scenarios even when one or the other of  $h_1$  or  $h_2$  dominates the  $gg \rightarrow \gamma\gamma$  rate, see the top right plot of Fig. 2. In comparison, double ratio II) is most useful for scenarios with  $R_{gg}^h(\gamma\gamma) \sim 1$ , as illustrated by the bottom left plot of Fig. 2.

What does current LHC data say about these various double ratios? The central values and  $1\sigma$  error bars<sup>2</sup> for the numerator and denominator of double ratios I) and II) obtained from CMS data [9] are also shown in Fig. 1.

<sup>1</sup> By “semi-unified” we mean universal gaugino mass parameter  $m_{1/2}$ , scalar (sfermion) mass parameter  $m_0$ , and trilinear coupling  $A_0 \equiv A_t = A_b = A_\tau$  at the GUT scale, but  $m_{H_u}^2$ ,  $m_{H_d}^2$  and  $m_S^2$  as well as  $A_\lambda$  and  $A_\kappa$  are taken as non-universal at  $M_{GUT}$ .

<sup>2</sup> For the ratio  $R_i/R_j$ , we use  $\sigma_i^{\text{upp,low}} = \frac{R_i}{R_j} \sqrt{(\sigma_i^{\text{upp,low}}/R_i)^2 + (\sigma_j^{\text{upp,low}}/R_j)^2}$  to calculate its combined asymmetric  $1\sigma$  error bar, where  $\sigma_i^{\text{upp,low}}$  is the upper/lower  $1\sigma$  error for the individual  $R_i$ .

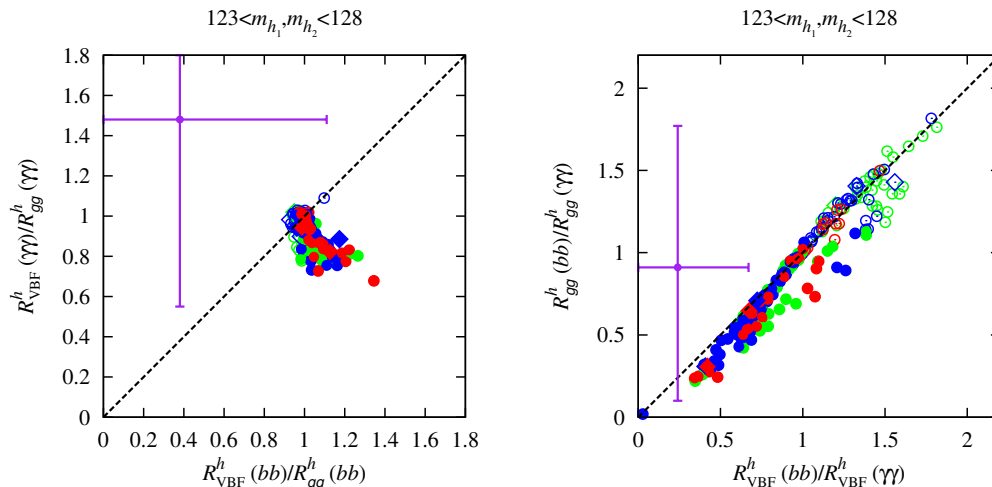


FIG. 1. Comparisons of pairs of event rate ratios that should be equal if only a single Higgs boson is present. The color code is green for points with  $2 \text{ GeV} < m_{h_2} - m_{h_1} \leq 3 \text{ GeV}$ , blue for  $1 \text{ GeV} < m_{h_2} - m_{h_1} \leq 2 \text{ GeV}$ , and red for  $m_{h_2} - m_{h_1} \leq 1 \text{ GeV}$ . Large diamond points have  $\Omega h^2$  in the WMAP window of  $[0.094, 0.136]$ , while circular points have  $\Omega h^2 < 0.094$ . Solid points are those with  $R_{gg}^h(\gamma\gamma) > 1$  and open symbols have  $R_{gg}^h(\gamma\gamma) \leq 1$ . Current experimental values for the ratios from CMS data along with their  $1\sigma$  error bars are also shown.

Obviously, current statistics are inadequate to discriminate whether or not the double ratios deviate from unity. About 100 times increased statistics will be needed. This will not be achieved until the  $\sqrt{s} = 14 \text{ TeV}$  run with  $\geq 100 \text{ fb}^{-1}$  of accumulated luminosity. Nonetheless, it is clear that our diagnostic tools will ultimately prove viable and perhaps crucial for determining if the  $\sim 125 \text{ GeV}$  Higgs signal is really only due to a single Higgs-like resonance or if two resonances are contributing, the latter having significant probability in model contexts if enhanced  $\gamma\gamma$  rates are indeed confirmed at higher statistics.

**To summarize**, we have emphasized the possibility that a  $\gamma\gamma$  Higgs-like signal that is significantly enhanced relative to the SM could arise as a result of there being two fairly degenerate Higgs bosons near 125 GeV. This situation arises in several model contexts in which the degeneracy can be such that separate mass peaks could not be observed in even the high-resolution  $\gamma\gamma$  and  $ZZ \rightarrow 4\ell$  final states. We have shown that deviations from unity of certain double ratios of event rates have strong potential for revealing the presence of two (or more) nearly degenerate Higgs bosons within the 125 GeV LHC signal. Such deviations arise when both the quasi-degenerate Higgses contribute significantly to at least one production/decay channel. We have employed the NMSSM as a prototype model to illustrate the discriminating power of these double ratios. Of course, substantial statistics will be required to reveal the deviations from unity that would signal a degenerate scenario.

## ACKNOWLEDGEMENTS

This work has been supported in part by US DOE grant DE-FG03-91ER40674 and by IN2P3 under contract PICS FR-USA No. 5872. JFG and SK thank the Aspen Center of Physics, where this work was completed, for hospitality and an inspiring working atmosphere.

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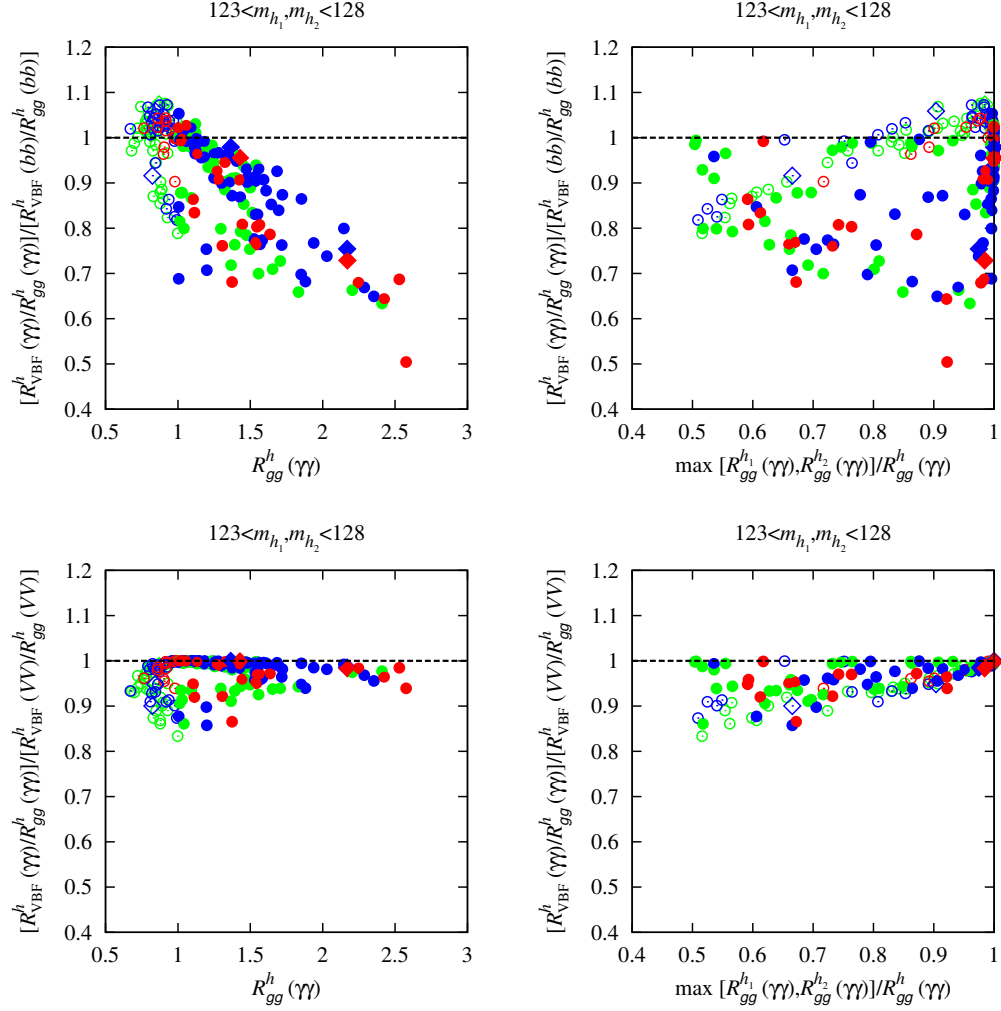


FIG. 2. Double ratios I) and II) of eq. (5) as functions of  $R_{gg}^h(\gamma\gamma)$  (on the left) and of  $\max[R_{gg}^{h_1}(\gamma\gamma), R_{gg}^{h_2}(\gamma\gamma)]/R_{gg}^h(\gamma\gamma)$  (on the right) for the points displayed in Fig. 1; colors and symbols are the same as in Fig. 1.

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